

# HOW IT WORKS

## Batteries and fuel cells

We take the humble battery for granted, but have you ever wondered how they work and if the design could be improved? Tom Royal gets charged up about portable power

**Y**ou probably use batteries all the time without even thinking about it. It's hard to imagine the modern home without them: there would be no clocks on the walls, no watches on our wrists, no digital cameras or camcorders, no personal stereos or MP3 players and no remote controls for anything. A notebook computer is useless without a battery, and even a desktop PC contains one tiny battery on its motherboard. This month, we'll explain how batteries work, and how fuel cells could keep you computing for days without needing to recharge.

As any neighbourhood pedant will tell you, usually at great length, most everyday batteries are not batteries at all. The type of battery that goes inside a remote control or torch is in fact a single cell, whereas the term battery refers to several cells used together. The battery in your car contains several cells, so it is truly a battery. Incidentally, wiring a pedant up to a car battery will persuade them that this distinction is usually meaningless. In this article we'll use the term battery to refer to all manner of cells, single or otherwise.

Batteries can be divided into two types: primary and secondary. Primary batteries are also known as Voltaic or disposable. The chemicals inside a primary battery react, producing electricity, but the process cannot be reversed. Secondary batteries are rechargeable. When electric current is passed through a secondary battery, the reaction that produces the current is reversed, storing energy for future use.

### PRIMARY COLOURS

One of the simplest primary batteries was invented in 1866. The Leclanché battery was named after its inventor, Georges Leclanché. His

original design was known as a wet battery, as it used a jar full of liquid ammonium chloride solution as the electrolyte. Over the years, this developed into the common zinc-carbon dry battery.

Where Leclanché's battery used a glass jar, modern zinc-carbon dry batteries use a zinc can. This is filled with a paste of ammonium chloride ( $\text{NH}_4\text{Cl}$ ), manganese dioxide ( $\text{MnO}_2$ ) and powdered graphite. A carbon rod is inserted into the paste. This rod forms the cathode of the circuit, while the zinc can acts as the anode. When something is connected between the cathode and the anode, two chemical reactions can take place. At the anode, zinc is oxidised, releasing two electrons. These flow around the circuit to the carbon cathode. At the carbon cathode, manganese dioxide is reduced, absorbing the electrons. Dry batteries produce around 1.5V, but have been largely superseded by alkaline batteries.

The alkaline battery was invented in 1959 by Lewis Urry, an engineer working for the Eveready company that now produces Energizer batteries. Unlike zinc-carbon batteries, where a zinc can is used as the anode, alkaline batteries use a steel can that connects to the cathode. Its inside is in contact with the outside of a tube made of manganese dioxide and carbon. The inside of this tube is coated in a porous separator, which is then filled with the powdered zinc anode. Potassium hydroxide solution is used as the electrolyte, and a brass pin in the centre connects the zinc powder to the battery's negative terminal. As in the zinc carbon battery, the zinc anode is oxidised, releasing electrons. These flow through the circuit to the cathode. This alkaline process is used in batteries such as

those sold by Energizer and Duracell. Manufacturers claim that alkaline batteries have up to 10 times the capacity of traditional zinc-carbon dry batteries.

### LEAD THE WAY

Zinc-carbon and alkaline batteries are convenient for many things, but both have one disadvantage in common: they use a chemical reaction that is not reversible. During use, the zinc casing of a zinc-carbon battery thins and the supply of ammonium ions diminishes. Eventually, it stops working and must be disposed of. This isn't a problem for devices such as a remote control, but imagine having to replace the battery in your notebook with a new one every day or two. For this reason secondary, or rechargeable, batteries are increasingly popular.

One of the simplest secondary battery systems is the lead-acid battery. Lead-acid batteries are too bulky for many applications, but they're still used to power car starter motors and uninterruptible power supply (UPS) systems.

A lead-acid car battery consists of six cells, each producing around 2V. Each cell consists of an anode made of lead (Pb), and a cathode made of lead oxide ( $\text{PbO}_2$ ). These are suspended in a liquid electrolyte made of sulphuric acid ( $\text{H}_2\text{SO}_4$  in water). When a load is applied, such as the ignition switch in a car being turned, the lead oxidises, producing lead sulphate and releasing electrons. These flow around the circuit to the cathode where the lead oxide plate is reduced, creating more lead sulphate and water.

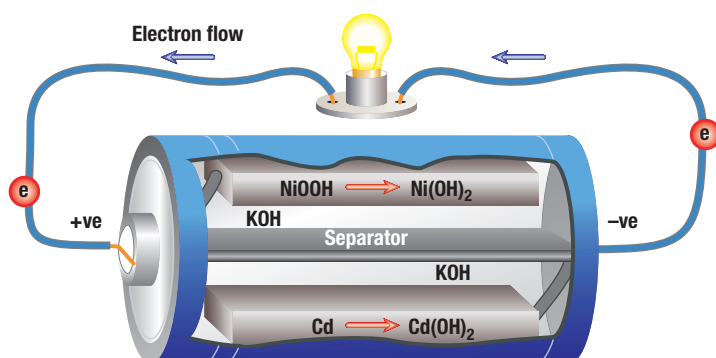
When a charging voltage is applied to the terminals of the battery – as the alternator does when the car is being driven – the process reverses. The lead sulphate is broken down, leaving the lead and lead oxide as they were and the battery recharged. Lead-acid batteries are simple and can produce the levels of current needed to turn a starter motor, but they're extremely heavy and impractical for use in most applications.

### NICKELS AND IONS

The nickel-cadmium (NiCad) battery was invented in 1899 by Waldemar Jungner as an alternative to lead-acid technology. It peaked in popularity during the 1990s, when nickel-cadmium batteries were used in all manner of consumer electrical products such as cordless phones and personal stereos. Over the past decade, however, their popularity has declined in favour of lithium-ion (li-ion) and nickel-metal hydride batteries, which can store more energy.

A NiCad battery uses a cadmium (Cd) anode and a nickel oxyhydroxide ( $\text{NiOOH}$ ) cathode, separated from one another and immersed in a

### Inside a nickel-cadmium battery



▲ The chemical reaction inside a nickel-cadmium rechargeable battery during use. When power is applied to the battery this process is reversed, charging it up

potassium hydroxide solution (see diagram below left). When a load is applied across the battery, cadmium at the anode is oxidised, producing cadmium hydroxide ( $\text{Cd}(\text{OH})_2$ ) and freeing electrons. These flow through the circuit to the cathode. Nickel oxyhydroxide is reduced at the cathode, producing nickel hydroxide ( $\text{Ni}(\text{OH})_2$ ). This produces approximately 1.2V.

Nickel metal hydride batteries have a similar composition, as they also use a nickel oxyhydroxide ( $\text{NiOOH}$ ) cathode and potassium hydroxide electrolyte. The anode is different, however. In a nickel-metal hydride battery it is made up of hydrogen in the form of a metal hydride. As the battery is discharged, this hydrogen is desorbed. The metal used in this alloy varies, but  $\text{LaNi}_5$ ,  $\text{TiMn}_2$  and  $\text{ZrMn}_2$  are common. Nickel-metal hydride batteries have a greater capacity than nickel-cadmium batteries. As they contain no cadmium, they are also considered to be more environmentally friendly.

### PERSISTENCE OF MEMORY

One common criticism of NiCad and nickel-metal hydride batteries is that they suffer from what is known as the memory effect. This effect apparently reduces the amount of charge that a nickel-based battery can hold, and is caused by not fully discharging the battery before recharging it. Some users will swear that devices they own have been destroyed by the memory effect, but others claim that there is no such problem with consumer batteries.

There is only one scientifically verified example of the memory effect. This has been observed on large, specialist sintered-plate nickel-cadmium batteries that are used to power satellites. It occurs when the battery is repeatedly fully charged and then discharged to a level where power is left in the battery. This level of discharge must be repeated exactly each time over multiple charge-and-discharge cycles for the phenomenon to be observed.

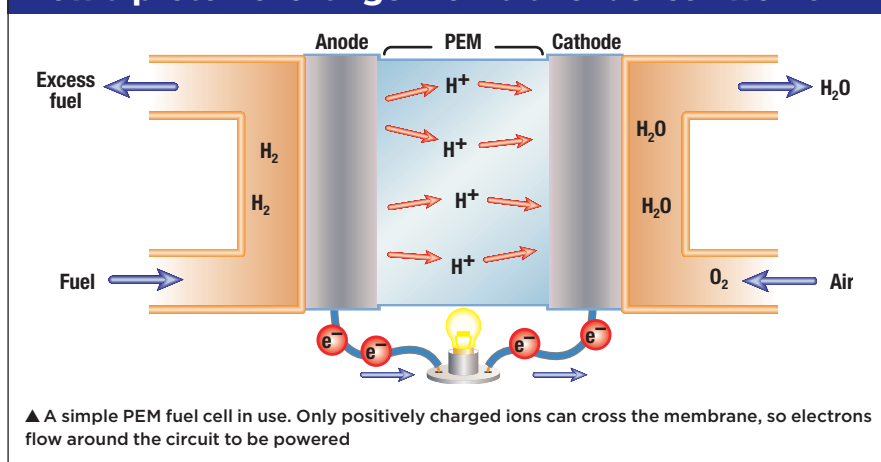
In fact, memory effect problems with consumer batteries are more commonly caused by a problem called voltage depression. When a nickel-based battery is repeatedly partially discharged and then recharged, crystals form inside the cell, increasing its internal resistance. This causes the voltage produced by the battery to drop faster than that of a battery that is always fully discharged before recharging. In experiments conducted by Duracell, a battery was fully discharged, recharged and then partially discharged and recharged 16 times. After this process it ran out of power in around 51 minutes, compared to the 55 minutes it achieved beforehand, giving the Duracell bunny less time to rush around.

Fortunately, voltage depression can usually be reversed by careful battery discharging and recharging. In Duracell's experiment, the battery had recovered to almost its original state after two full discharge-and-recharge cycles.

### SWEET LITTLE LI

Nickel-metal hydride batteries are commonly used in small household items, but it's more rare to find one powering a modern notebook computer or mobile phone. Instead, most advanced electronic devices available today use batteries based on lithium. Lithium is the lightest metal, so lithium batteries weigh very little. This

## How a proton exchange membrane fuel cell works



makes them ideal for use in notebook computers and mobile phones.

Li-ion batteries use a cathode made of lithium cobalt oxide ( $\text{LiCoO}_2$ ) or lithium manganese, and an anode made of crystallised carbon ( $\text{C}_6$ ). When charging, lithium moves between the layers of crystallised carbon, forming a lithium carbon compound. When discharging, the anode is oxidised, freeing lithium ions and an electron. The electron travels around the circuit to the cathode. At the cathode the lithium cobalt oxide is reduced, absorbing the lithium ion and the electron. Newer rechargeable batteries, known as li-ion polymer or lithium polymer batteries, use a similar chemistry but a different structure that allows the battery to be made smaller.

Li-ion batteries hold an impressive amount of energy, but they have some disadvantages. Most importantly, they lose their ability to hold a charge over a period of years. The rate of this deterioration is affected by temperature, so a battery stored in a hot location loses charge more quickly than one that is kept cool. Li-ion batteries must also incorporate complicated protection mechanisms that monitor the battery temperature in order to prevent it overheating and potentially exploding.

Stories of camera and mobile phone batteries exploding are commonplace. Most involve cheaper non-original or counterfeit batteries, but all are extremely hard to verify. Two well-known stories involve counterfeit batteries for Nokia mobile phones and Nikon D70 digital cameras. When we contacted Nokia, we were told that "there have been previous exploding battery cases in the world and in all these cases the malfunctioning battery has been a non-original

battery". It did not provide information on any specific explosions. Nikon told us it was aware of reports "about some counterfeit batteries overheating" but that it was "unaware of any prosecutions taking place" with regard to these incidents.

### SOFT CELL

The best lithium-based notebook batteries we've seen can keep a computer running for five or six hours before needing to be recharged. This is impressive, but it's some way off a full working day, let alone a week-long business trip. Some companies are looking at a different technology, the fuel cell, as the answer.

A fuel cell is a little like a primary battery in that it produces electricity from a one-way chemical reaction. Unlike most primary cells, though, it can be refuelled by adding more chemicals to its fuel tank. Several fuel cell designs are currently in development, and the proton exchange membrane system is one of the most popular.

The proton exchange membrane system combines hydrogen and oxygen to produce water and electric current. It uses an anode and cathode separated by a special membrane that allows only protons to pass through. Hydrogen reaches the anode, which is coated in a platinum catalyst, and splits. Positive hydrogen ions go through the membrane to the cathode, leaving electrons behind. These flow out and through the circuit, finally reaching the cathode. At the cathode, also covered in a catalyst, the hydrogen ions, electrons and oxygen from the air combine to produce water. This water, either as liquid or vapour, is the only by-product of the process. A stack comprising many such cells in series is used to create a usable voltage.

Several prototypes of such a fuel cell have been demonstrated. In 2004, Toshiba demonstrated a tiny methanol fuel cell capable of powering an MP3 player or mobile phone. Methanol fuel cells use a process very similar to the proton exchange membrane system described above. The fuel used is methanol mixed

with water. At the anode, positive hydrogen ions pass through the membrane and electrons flow through the circuit. The remainder of the fuel is left as carbon dioxide.

The idea that fuel cells will soon replace batteries in notebook computers has been suggested for years, but to date no such computer has been produced. It seems likely, though, that within the next decade you'll be able to refuel your notebook at the airport without waiting hours for its battery to recharge. ☑

### FURTHER READING

**Diagram of li-ion battery**  
[www.electronics-lab.com/articles/Li Ion\\_reconstruct](http://www.electronics-lab.com/articles/Li Ion_reconstruct)

**How PEM fuel cells work**  
[www.fueleconomy.gov/feg/fcv\\_pem.shtml](http://www.fueleconomy.gov/feg/fcv_pem.shtml)

**Toshiba's prototype fuel cell**  
<http://news.bbc.co.uk/2/hi/technology/3837585.stm>

**Voltage depression test**  
[www.duracell.com/oem/pdf/others/nimh\\_5.pdf](http://www.duracell.com/oem/pdf/others/nimh_5.pdf)